# Dynamical Electroweak Symmetry Breaking: Implications of the H(126) DRAFT

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**Abstract**



## 1 Introduction

In theories of dynamical electroweak symmetry breaking, the electroweak interactions are broken to electromagnetism by the vacuum expectation value of a composite operator, typically a fermion bilinear. In these theories the longitudinal components of the massive weak bosons are identified with composite Nambu-Goldstone bosons arising from dynamical symmetry breaking in a strongly-coupled extension of the standard model. Viable theories of dynamical electroweak symmetry breaking must also explain (or at least accommodate) the presence of an additional composite scalar state to be identified with the H(126) scalar boson [1, 2] – a state unlike any other observed to date.

Theories of dynamical electroweak symmetry breaking can be classified by the nature of the composite singlet state to be associated with the H(126), and the corresponding scale $\Lambda$ of the underlying strong dynamics. The basic possibilities, and the additional states that they predict, are described below.

- **Technicolor,** $\Lambda \simeq 1$ **TeV**: Technicolor models [3, 4, 5] incorporate a new asymptotically free gauge theory ("technnicolor") and additional massless fermions ("technifermions" transforming under a vectorial representation of the gauge group). The global chiral symmetry of the fermions is spontaneously broken by the formation of a technifermion condensate, just as the approximate chiral symmetry in QCD is broken down to isospin by the formation of a quark condensate. The $SU(2)_W \times U(1)_Y$ interactions are embedded in the global technifermion chiral symmetries in such a way that the only unbroken gauge symmetry after chiral symmetry breaking is $U(1)_{em}$.[1] These theories naturally provide the Nambu-Goldstone bosons "eaten" by the $W$ and $Z$ boson, and there are various possibilities for the scalar H(126) as described below.

In these theories there would typically be additional states (e.g. vector mesons, analogous to the $\rho$ and $\omega$ mesons in QCD) with TeV masses [9, 10], and the $WW$ and $ZZ$ scattering amplitudes would expected to be strong at energies of order 1 TeV. In all of these cases, however, to the extent that the H(126) has couplings consistent with those of the standard model, these theories are highly constrained.

1. **H(126) as a singlet scalar resonance**: The strongly-interacting fermions which make up the Nambu-Goldstone bosons eaten by the weak bosons would naturally be expected to also form an isoscalar neutral bound state, analogous to the $\sigma$ particle expected in pion-scattering in QCD [11]. However, in this case there is no symmetry protecting the mass of such a particle – which would therefore generically be of order the energy scale of the underlying strong dynamics $\Lambda$. In the simplest theories of this kind – those with a global $SU(2)_L \times SU(2)_R$ chiral symmetry which is spontaneously broken to $SU(2)_V$ – the natural dynamical scale $\Lambda$ would be of order a TeV, resulting in a particle too heavy to be identified with the H(126).[2] The scale of the underlying interactions could naturally be smaller than 1 TeV if the global symmetries of the theory are larger than $SU(2)_L \times SU(2)_R$, but in this case there would be additional (pseudo-)Nambu-Goldstone bosons (more on this below). A theory of this kind would only be viable, therefore, if some choice of the parameters of the high energy theory could give rise to sufficiently light state without the appearance of additional particles that should have already been observed. Furthermore, while a particle with these quantum numbers could have Higgs-like couplings to any electrically neutral spin-zero state made of quarks, leptons, or gauge-bosons, there is no symmetry insuring that the coupling strengths of such a composite singlet scalar state would be precisely the same as those of the standard model Higgs.
2. **H(126) as a dilaton**: It is possible that the underlying strong dynamics is approximately scale-invariant, as inspired by theories of "walking technicolor" [13, 14, 15, 16, 17], and that both the scale and electroweak symmetries are spontaneously broken at the TeV energy scale [27]. In this case, due to the spontaneous breaking of approximate scale invariance, one might expect a corresponding (pseudo-)Nambu-Goldstone boson with a mass less than a TeV, the dilaton.[3] A dilaton couples to the trace of the energy momentum tensor, which leads to precisely the same pattern of two-body couplings as the standard model Higgs boson [23, 24, 25]. Scale-invariance is a space-time symmetry, however, and by the Coleman-Mandula theorem [26] we know that space-time symmetries cannot be embedded in a larger symmetry which includes the global symmetries that we can identify with the electroweak group. There is no reason, therefore, that the decay-constants associated with the breaking of the scale and electroweak symmetries will be precisely the same.[4] In other words, if there are no large anomalous dimensions associated with the $W$- and $Z$-bosons or the top- or bottom-quarks, the ratios of the

[1] For a review of technicolor models, see [6, 7, 8].

[2] See [12], for an alternative viewpoint.

[3] Even in this case, however, a dilaton associated with electroweak symmetry breaking will likely not *generically* be as light as the H(126) [19, 20, 21, 22].

[4] Even in a weakly-coupled, but approximately scale-invariant, theory of electroweak symmetry breaking one expects that the decay-constants of the electroweak and scale currents will differ at higher order in perturbation theory [27].

couplings of the dilaton to these particles would be the same as the ratios of the same couplings for the standard model Higgs boson, but the overall strength of the dilaton couplings would be expected to be different [28, 29]. Furthermore, the couplings of the dilaton to gluon- and photon-pairs can be related to the beta functions of the corresponding gauge interactions in the underlying high-energy theory, and will not in general yield couplings with the exactly the same strengths as the standard model.

3. **H(126) as a singlet Pseudo-Nambu-Goldstone Boson**: If the global symmetries of the technicolor theory are larger than $SU(2)_L \times SU(2)_R$, there can be extra singlet (pseudo-)Nambu-Goldstone bosons which could be identified with the H(126). In this case, however, the coupling strength of the singlet state to $WW$ and $ZZ$ pairs would be comparable to the couplings to gluon and photon pairs, and these would all arise from loop-level couplings in the underlying technicolor theory [30]. This pattern of couplings is not supported by the data.

- **Electroweak Symmetry Breaking Through Vacuum (Mis-)Alignment, $\Lambda > 1$ TeV**: In technicolor models, the symmetry breaking properties of the underlying strong dynamics necessarily breaks the electroweak gauge symmetries. An alternative possibility, is that the underlying strong dynamics itself does not break the electroweak interactions, and that the entire quartet of bosons in the Higgs doublet (including the state associated with the H(126)) are composite (pseudo-)Nambdu-Goldstone particles [31, 32]. In this case the underlying dynamics can occur at energies larger than 1 TeV and additional interactions, typically additional weakly-coupled gauge-interactions, are present which cause the vacuum energy to be minimized when the composite Higgs doublet gains a vacuum expectation value [33]. In these theories the couplings of the remaining singlet scalar state would naturally be equal to that of the standard model Higgs boson up to corrections of order $(1\,\mathrm{TeV}/\Lambda)^2$ and, therefore, constraints on the size of deviations of the H(126) couplings from that of the standard model Higgs give rise to lower bounds on the scale $\Lambda$.

  The electroweak gauge-interactions as well as the interactions responsible for the top-quark mass explicitly break the chiral symmetries of the composite Higgs model, and lead generically to sizable corrections to the mass-squared of the Higgs-doublet – the so-called "Little Hierarchy Problem" [34]. "Little Higgs" theories [35, 36, 37, 38] are examples of composite Higgs models in which the (collective) symmetry breaking structure is selected so as to suppress these contributions to the Higgs mass-squared while allowing for a sufficiently large Higgs-boson self-coupling. The collective symmetry breaking required in Little Higgs models typically requires a larger global symmetry of the underlying theory, and hence additional relatively light (compared to $\Lambda$) scalar particles, extra electroweak vector bosons (e.g. an additional $SU(2) \times U(1)$ gauge group), and vectorial partners of the top-quark of charge $+2/3$ and possibly also $+5/3$ [39]. Finally, in addition to these states, one would expect the underlying dynamics to yield additional scalar and vector resonances with masses of order $\Lambda$.

- **Top-Condensate, Top-Color, Top-Seesaw and related theories, $\Lambda > 1$ TeV**: A final alternative is to consider a strongly interacting theory with a high (compared to a TeV) underlying dynamical scale that *would* naturally break the electroweak interactions, but whose strength is adjusted ("fine-tuned") to produce electroweak symmetry breaking at 1 TeV. This alternative is possible if the electroweak (quantum) phase transition is continuous (second order) in the strength of the strong dynamics [40]. If the fine-tuning can be achieved, the underlying strong interactions will produce a light composite Higgs bound state with couplings equal to that of the standard model Higgs boson up to corrections of order $(1\,\mathrm{TeV}/\Lambda)^2$.

As in theories in which electroweak symmetry breaking occurs through vacuum alignement, therefore, constraints on the size of deviations of the H(126) couplings from that of the standard model Higgs give rise to lower bounds on the scale $\Lambda$. Formally, in the limit $\Lambda \to \infty$ (a limit which requires arbitrarily fine adjustment of the strength of the high-energy interactions), these theories are equivalent to a theory with a fundamental Higgs boson – and the fine adjustment of the coupling strength is a manifestation of the hierarchy problem of theories with a fundamental scalar particle.

In many of these theories the top-quark itself interacts strongly (at high energies), potentially through an extended color gauge sector [41, 42, 43, 44]. In these theories, top-quark condensation (or the condensation of an admixture of the top with additional vector quarks) is responsible for electroweak symmetry breaking, and the H(126) is identified with a bound state involving the third generation of quarks. These theories typically include an extra set of massive color-octet vector bosons (top-gluons), and an extra $U(1)$ interaction (giving rise to a top-color Z') which couple preferentially to the third generation and whose masses define the scale $\Lambda$ of the underlying physics.

In addition to the electroweak symmetry breaking dynamics described above, which gives rise to the masses of the $W$ and $Z$ particles, additional interactions must be introduced to produce the masses of the standard model fermions. Two general avenues have been suggested for these new interactions. In one case, e.g. "extended technicolor" theories [45, 46], the gauge-interactions in the underlying strongly interacting theory are extended to incorporate flavor. This extended gauge symmetry is broken down (possibly sequentially, at several different mass scales) to the residual strongly-interacting interaction responsible for electroweak symmetry breaking. The massive gauge-bosons corresponding to the broken symmetries then mediate interactions between mass operators for the quarks/leptons and the corresponding bilinears of the strongly-interacting fermions, giving rise to the masses of the ordinary fermions after electroweak symmetry breaking. An alternative proposal, "partial compositeness" [47], postulates additional interactions giving rise to mixing between the ordinary quarks and leptons and massive composite fermions in the strongly-interacting underlying theory. Theories incorporating partial compositeness include additional vectorial partners of the ordinary quarks and leptons, typically with masses of order a TeV or less.

In both cases, the effects of these flavor interactions on the electroweak properties of the ordinary quarks and leptons are likely to be most pronounced in the third generation of fermions.[5] The additional particles present, especially the additional scalars, often couple more strongly to heavier fermions. Moreover, since the flavor interactions must give rise to quark mixing, we expect that a generic theory of this kind could give rise to large flavor-changing neutral-currents [46] – though these constraints are typically somewhat relaxed if the theory "walks" [13, 14, 15, 16, 17] or if $\Lambda > 1$ TeV [48]. For these reasons, most authors assume that the underlying flavor dynamics respects flavor symmetries ("minimal" [49, 50] or "next-to-minimal" [51] flavor violation) which suppress flavor-changing neutral currents in the two light generations. Additional considerations apply when extending these considerations to potential explanation of neutrino masses [52].

Since the underlying high-energy dynamics in these theories is strongly-coupled, there are no reliable calculation techniques that can be applied to analyze their properties. Instead, most phenomeno-

[5] Indeed, from this point of view, the vectorial partners of the top-quark in top-seesaw and little Higgs models can be viewed as incorporating partial compositeness to explain the origin of the top quark's large mass.

logical studies depend on the construction of a "low-energy" effective theory describing additional scalar, fermion, or vector boson degrees of freedom, which incorporates the relevant symmetries and, when available, dynamical principles. In some cases, motivated by the AdS/CFT correspondence [53], the strongly-interacting theories described above have been investigated by analyzing a dual compactified five-dimensional gauge theory. In these cases, the AdS/CFT "dictionary" is used to map the features of the underlying strongly-coupled high-energy dynamics onto the low-energy weakly-coupled dual theory [54].

More recently, progress has been made in investigating strongly-coupled models using lattice gauge theory [55, 56]. These calculations offer the prospect of establishing which strongly coupled theories of electroweak symmetry breaking have a particle with properties consistent with those observed for the H(126) – and for establishing concrete predictions for these theories at the LHC [57].

# 2 Experimental Searches

As discussed above, the extent to which the couplings of the H(126) conform to the expectations for a standard model Higgs boson constrains the viability of each of these models. Measurements of the H(126) couplings, and their interpretation in terms of effective field theory, are summarized in the H(126) review in this volume. In what follows we will focus on searches for the additional particles that might be expected to accompany the singlet scalar - extra scalars, fermions, and vector bosons. In some cases, detailed model dependent searches have been made for the particles described above in specific models (though generally not yet taking account of the demonstrated existence of the H(126) boson). In most cases, however, generic searches (e.g. for extra $W'$ or $Z'$ particles, extra scalars in the context of multi-Higgs models, or for fourth-generation quarks) are quoted which can be used - when appropriately translated - to derive bounds on a specific model of interest.

The mass reach required means that only the Large Hadron Collider has real sensitivity. A number of analyses already carried out by ATLAS and CMS use relevant final states and might have been expected to observe a deviation from standard model expectations - in no case so far has any such deviation been reported. Given the discovery of the H(126) and the need to pin down how it behaves, we expect that such analyses will be a feature of the next run of the LHC; the higher centre of mass energy of collisions will open up an increased reach for discovery.

## 2.1 $W'$ or $Z'$ Bosons

Massive vector bosons or particles with similar decay channels would be expected to arise in Little Higgs theories, in theories of Technicolor, or models involving a dilation, adjusted to produce a light Higgs consistent with the observed H(126). These particles would be expected to decay to pairs of vector bosons, to third generation quarks, or to leptons. The generic searches for $W'$ and $Z'$ vector bosons listed below can, therefore, be used to constrain models incorporating a composite Higgs-like boson.

ATLAS [ATLAS-CONF-2013-017] has searched for $Z'$ production with $Z' \to ee$ or $\mu\mu$ in 20 $\text{fb}^{-1}$ of collision data recorded at $\sqrt{s} = 8$ TeV. No deviation from the standard model prediction is seen, and mass limits on possible $Z'$ particles are set at 2.86 TeV for a sequential $Z'$, $2.38 - 2.54$ TeV for various $E6$-motivated bosons, and 2.47 TeV for a Randall-Sundrum graviton with coupling parameter $k = M_{Pl}$ equal to 0.1.

CMS [CMS-PAS-EXO-12-061] has also performed searches for a heavy $Z'$ decaying to $ee$ or $\mu\mu$ final states using 20.6 $\text{fb}^{-1}$ of data collected during the 2012 run of the LHC. In the absence of a excess above the expected background in the di-electron and dimuon invariant mass spectra, mass limits on a Sequential Standard Model $Z'_{\text{SSM}}$ and a superstring-inspired $Z'_{\psi}$ are set at 2.96 TeV and 2.6 TeV respectively.

ATLAS [ATLAS-CONF-2013-052] has also searched for $Z'$ decaying into top quark pairs using $14\,\text{fb}^{-1}$ of collision data collected at $\sqrt{s} = 8$ TeV. The lepton plus jets final state is used, where the top-pair decays as $t\bar{t} \to WbWb$ with one W boson decaying leptonically and the other hadronically. The $tt$ invariant mass spectrum is analyzed for any local excess, and no evidence for any resonance is seen. Upper limits are set on the cross section times branching ratio of a narrow $Z'$ boson decaying to top pairs ranging from 5.3 pb for a $Z'$ mass of 0.5 TeV to 0.08 pb for a mass of 3 TeV. A narrow leptophobic topcolor $Z'$ boson with a mass below 1.8 TeV is excluded, and upper limits are also set on the cross section times branching ratio for a broad color-octet resonance with $\frac{\Gamma,m}{=}15.3\%$ decaying to $tt$ which range from 9.6 pb for a mass of 0.5 TeV to 0.152 pb for a mass of 2.5 TeV.

CMS [CMS-PAS-B2G-12-006] has carried out a similar search for $Z'$ resonances decaying to $t\bar{t}$ pairs, using semileptonic decays of the top quarks. The analysis considers $t\bar{t}$ events both at the kinematic production threshold, and those produced with high Lorentz boosts. No resonant structure above SM background is observed and upper limits on the production cross section times branching ratio for narrow (wide) resonances are set at 1.94(1.71) pb for a mass of 0.5 TeV and 0.029(0.045) pb for a mass of 2 TeV. Topcolor $Z'$ bosons with masses below 2.1 TeV and 2.7 TeV are excluded for relative widths of 1.2% and 10% respectively. In the Randall-Sundrum model, the Kaluza-Klein excitations of a gluon with masses below 2.5 TeV are excluded and for a resonance mass of 2 TeV.

CMS [CMS-PAS-EXO-12-023] has additionally searched for heavy $Z'$ resonances decaying to the $b\bar{b}$ final state by selecting event with dijets where one or both of the jets is tagged as a $b$-quark. The search is performed using 19.6 $\text{fb}^{-1}$ of data collected at $\sqrt{s}$=8 TeV and is able to exclude a sequential standard model $Z' \to b\bar{b}$ with a mass between 1.20 and 1.68 TeV, when the decay branching fraction of $Z' \to b\bar{b}$ is taken to be 0.22.

Both LHC experiments have also searched for massive charged vector bosons. ATLAS [ATLAS-CONF-2013-015] has searched for a resonant $W'$ state decaying to $WZ$ in the fully leptonic channel, $\ell\nu\ell'$ (where $\ell, \ell' = e, \mu$). The analysis used 13 $\text{fb}^{-1}$ recorded at $\sqrt{s} = 8$ TeV. No significant localized excess is observed in the reconstructed $WZ$ invariant mass distribution. Upper limits on the production cross section times branching ratio are derived and a bound on the $W'$ mass of 1.18 TeV is obtained in the context of benchmark Extended Gauge models.

CMS [CMS-PAS-EXO-12-025] searched for $W'$ at $\sqrt{s} = 7$ and 8 TeV using the decay mode $W' \to WZ \to \ell\ell\ell\nu$ (with $\ell = e, \mu$) final state [**?**, **?**]. Using a sample of 19.6 $\text{fb}^{-1}$ of data, CMS excludes a $W'$ with masses between 0.17 and 1.450 TeV. CMS [CMS-PAS-EXO-12-024] also performed a search for $W' \to WZ$ using dijet events, where one of both of the jets maybe be identified as a W or a $Z$ boson using a jet-substructure technique. In the absence of any excess, a $W'$ decaying into $WZ$ is excluded up to 1.73 TeV at 95% CL.

Searches by CMS [CMS-PAS-EXO-12-060] for a heavy $W'$ decaying to $e\nu or \mu\nu$ again yield a null signal, allowing a SM-like $W'$ with masses up to 3.35 TeV to be excluded. This result can be re-interpreted to rule out a split UED Kaluza-Klein $W^2_{KK}$ excitation below 3.7 TeV for the mass parameter $\mu$=10 TeV, and in addition set a limit on the scale of any new four-fermion contact interaction $\Lambda$ of 13.0(10.9) TeV for the electron(muon) channel. *(use table 3 of the note.)?*

Heavy new gauge bosons can couple to left-handed fermions like the $W$ boson or to right-handed fermions. $W'$ bosons that couple only to right-handed fermions may not have leptonic decay modes, depending on the mass of the right-handed neutrino. For these $W'$ bosons, the $tb$ decay mode is especially important because it is the hadronic decay mode with the best signal-to-background. CMS [CMS-PAS-B2G-12-010] has carried out a search for $W' \to tb$ decays followed by $t \to bW$ and $W \to \ell\nu$. The analysis relies on the invariant mass of the $W'$, using $\ell\nu$+jets events with one or more $b$-tags and uses multivariate techniques to improve signal to background separation. The measurement is carried out for arbitrary combinations of the coupling strengths of the $W'$ to left and right handed fermions. Based on an analysis of 19.6 $\mathrm{fb}^{-1}$ of data, $W'$ bosons with purely left-handed (right-handed) couplings to fermions are excluded for masses below 2.09(2.03) TeV. ATLAS [ATLAS-CONF-2013-050] has also searched for $W'$ bosons in single-top production, using 14.3 $\mathrm{fb}^{-1}$ of data recorded at $\sqrt{s} = 8$ TeV. The analysis looks at the $\ell\nu b\bar{b}$ final state ($\ell = e, \mu$) again using a multivariate method. No significant deviation from the Standard Model expectation is observed and for a left-handed (right-handed) $W'$ boson, masses below 1.74 (1.84) TeV are excluded at the 95% confidence level.

### 2.2 Technicolor Resonances

While the $W$" and $Z'$ searches listed above have not been interpreted in terms of specific technicolor models, the technicolor-inspired searches listed here have been carried out at the LHC.

ATLAS has searched for a dijet resonance[**?**] with an invariant mass in the range 130 - 300 GeV produced in association with a $W$ or $Z$ boson. The analysis used 20.3 $\mathrm{fb}^{-1}$ of data recorded at $\sqrt{s}$ = 8 TeV. The W/Z are required to decay leptonically ($\ell = e, \mu$). No significant deviation from the Standard Model prediction is observed and limits are set on the production cross section times branching ratio for a hypothetical technipion produced in association with a $W$ or $Z$ boson from the decay of a technirho particle in the context of Low Scale Technicolor models.

Both ATLAS and CMS searches for a resonant $W'$ state decaying to$WZ$ in the fully leptonic channel, $\ell\nu\ell'(\ell, \ell' = e, mu)$, described earlier[**?**, **?**], has also been used to place limits on a technirho decaying to WZ in similar models.

### 2.3 Vector third generation quarks

Vector partners of the third generation of quarks arise in Little Higgs theories, and theories of a composite Higgs with partial compositeness.

CMS has performed a search targeted on vector-like charge 2/3 $T$ quarks that decay exclusively to $tZ$ based on an integrated luminosity of 1.1 $\mathrm{fb}^{-1}$ from pp collisions at $\sqrt{s} = 7$ TeV [?]. Selected events must have three isolated charged leptons, two of which must be consistent with a leptonic $Z$-boson decay. No significant excess was observed. $T$ quark masses below 485 GeV are excluded at 95% CL.

Another targeted search for heavy charge 1/3 $B$ quarks which decay exclusively to bZ has been performed by CMS [?]. The events selected must have two isolated charged leptons, consistent with the leptonic decay of a $Z$ boson and at least one jet identified as originating from a b quark. The signal would appear as a local enhancement in the mass spectrum of the Z boson and the highest $p_T$ b quark jet. No such signal is observed. $B$ quark masses below 700 GeV are excluded at 95% CL. This analysis also sets an upper limit on the branching fraction of $B$ quarks to decay to bZ of 30-100% in the $B$ quark mass range 450-700 GeV at 95% CL.

CMS has searched for pair production of heavy charge 2/3 $T$ quarks that decay exclusively to $bW$ [?] based on the data collected at $\sqrt{s} = 7$ TeV in 2011 with an integrated luminosity of 5 $\mathrm{fb}^{-1}$. The analysis selects events with exactly one charged lepton, assuming that the $W$ boson from the second $T$ quark decays hadronically. Under this hypothesis a 2C kinematic fit can be performed to reconstruct the mass of the $T$ quark. The two-dimensional distribution of reconstructed mass vs HT, the scalar sum of lepton $p_T$, missing $p_T$, and the leading four jet $p_T$s, is used to test for the signal. No excess over standard model backgrounds is observed. This analysis excludes new quarks that decay 100% to $bW$ for masses below 570 GeV at 95% CL.

CMS has extended this analysis under the hypothesis of a chiral fourth generation with an electroweak doublet of $t'$ and $b'$ quarks, that are approximately degenerate in mass, as favored by precision electroweak measurements [?]. This analysis considers pair production and single production of $t'$ and $b'$ quarks. The event selection include final states with more than one charged lepton and classifies single lepton events according to the number of $W$ boson decays and b-quark induced jets observed. Assuming that the new 4th generation only mixes with the 3rd generation and in the limit of small mixing this analysis excludes chiral 4th generation up-type quarks with masses below 685 GeV at 95% CL. The limit increases with increased mixing.

ATLAS has searched for the production of a heavy top-like quark (T) together with its antiparticle, assuming a significant branching ratio for subsequent decay into a $W$ boson and a b quark [?]. The search is based upon 14.3 $\mathrm{fb}^{-1}$ of data recorded at $\sqrt{s} = 8$ TeV. It uses the lepton+jets final state and is optimized for $T$ masses above about 400 GeV by requiring a high boost of the $W$ decay products. No significant excess of events above the Standard Model expectation is observed. For a chiral fourth generation quark, and for branching ratio $BR(T \to Wb) = 1$, masses lower than 740 GeV are excluded. For vector-like $T$ quarks limits are set in the two-dimensional plane of $BR(T \to Wb)$ versus $BR(T \to Ht)$, see Fig. 1 (left) panel) and excludes vector-like $T$ quarks with masses in the range 350-550 GeV.

ATLAS has carried out a complementary search for new heavy quarks decaying into a $Z$ boson and a third generation quark [?]. The analysis targets both a new charge +2/3 quark T, with $T \to Zt$, and a new charge -1/3 quark B, with $B \to bZ$. The search uses 14.3 fb$^{-1}$ of data recorded at $\sqrt{s}$=8 TeV. Selected events contain a high transverse momentum $Z$ decaying leptonically, together with two b-jets. No significant excess of events above the Standard Model expectation is observed, and mass limits are set depending on the assumed branching ratios, see Fig. 1 (right panel). In a weak-isospin singlet scenario, a $T$ (B) quark with mass lower than 585 (645) GeV is excluded at the 95% confidence level, while for a particular weak-isospin doublet scenario, a $T$ ($B$) quark with mass lower than 680 (725) GeV is excluded.

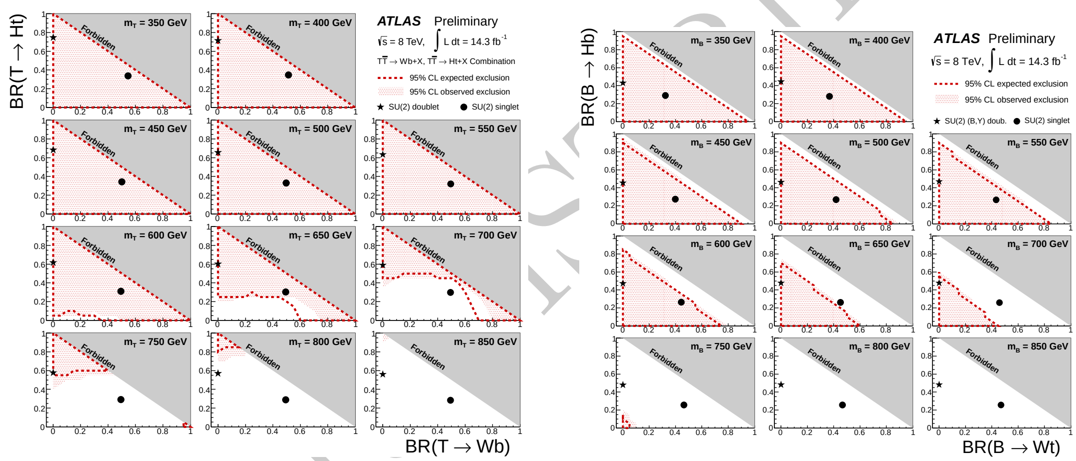


Figure 1: Exclusion limits at 95% C.L. for $TT$ pair production in the $BR(T \to Wb)$ versus $BR(T \to Ht)$ plane (left panel), and for the case of $BB$ pair production in the $BR(B \to Wt)$ versus $BR(B \to Ht)$ (right panel) for $B$ and $T$ quark masses between 350-850 GeV. The plain circle and star symbols denote the default branching ratios for the weak-isospin singlet and doublet cases [?].

CMS has performed a inclusive search that is more generally targeted at heavy charge 2/3 quarks $T$ that decay to any combination of bW, tZ, or tH [?]. This analysis is based on the data collected at $\sqrt{s} = 8$ TeV in 2012 with an integrated luminosity of 19.5 fb$^{-1}$. In this inclusive search, selected events have at least one isolated charged lepton. Events are categorized according to number and flavour of the leptons, the number of jets and the presence of hadronic vector boson and top quark decays that are merged into a single jet. The use of jet substructure to identify hadronic decays significantly increases the acceptance for high $T$ quark masses. The analysis of the high-background single lepton channels is based on a multivariate algorithm using Boosted Decision Trees. The analysis of the low background multilepton channels is based on the event counts in the individual channels. No excess above standard model backgrounds is observed. Limits on the pair production cross section of the new quarks are set, combining all event categories, for all combinations of branching fractions into the three final states. For $T$ quarks that exclusively decay to $bW/tZ/tH$, masses below 700/782/706 GeV are excluded at 95% CL. Electroweak singlet vector-like $T$ quarks which decay 50% to $bW$, 25% to $tZ$, and 25% to $tH$ are excluded for masses below 696 GeV.

The CMS analysis also quotes 95% CL limits between 690 and 782 GeV on the mass of the $T$ quark for all possible values of the branching fractions into the three different final states $bW, tZ$ and $tH$. The 95% CL observed limit for all combination of the three branching fractions is shown in Fig. 2 (left panel). Every point in the triangle corresponds to a particular set of branching fraction values for $T \rightarrow bW$, $tZ$ and $tH$. such that all three add up to one. In Fig. 2 (right panel) the 95% CL cross section limit is plotted for the nominal combination of branching fractions (50% to bW, 25% to tZ, and 25%).

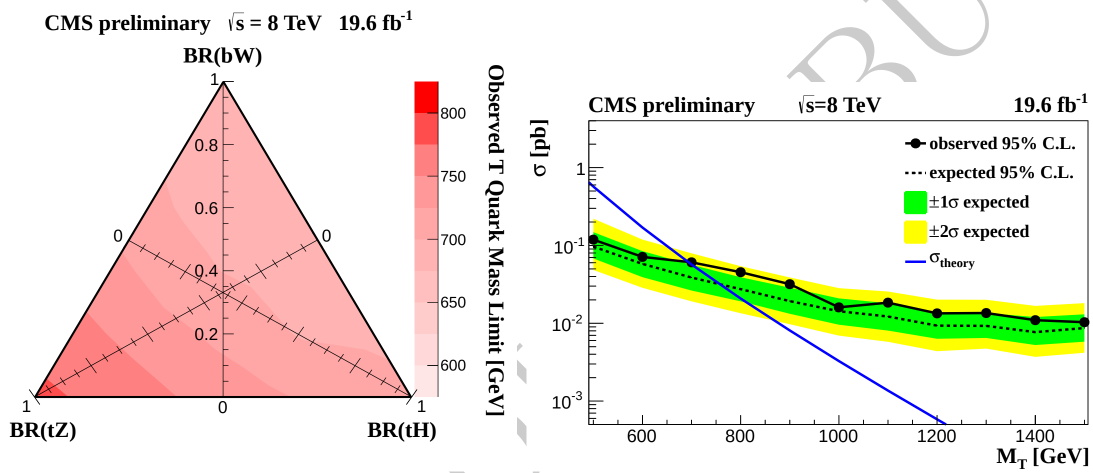


Figure 2: Branching fraction triangle with observed limits for the $T$ quark mass is shown on the left panel. The 95% C.L. upper limits on the $T$ quark production cross section for branching fractions into bW, tH, tZ of 50%, 25%, 25% us shown on the right panel. [?].

## 2.4 A charge +5/3 top-partner quark

In models of dynamical electroweak symmetry breaking, the same interactions which give rise to the mass of the top-quark can give unacceptably large corrections to the branching ration of the $Z$ boson to $b\bar{b}$ [58]. These corrections can be substantially reduced, however, in theories with an extended "custodial symmetry" [39]. This symmetry requires the existence of a charge +5/3 vectorial partner of the top quark.

CMS has performed a search for heavy top with exotic charge 5/3, $T_{5/3}$ vector-like quark following the models in Refs. [?, ?]. CMS has searched for the pair-production of $\mathrm{T}_{5/3}$ with $\mathrm{T}_{5/3}$ decays to $tW$ with a 100% decay rate. It is assumed that $\mathrm{T}_{5/3}$ is heavier than the B The analysis is based on searching for same-sign leptons, from the two $W$s from one of the $\mathrm{T}_{5/3}$. Requiring same-sign leptons eliminates most of the SM background processes, leaving those smaller cross sections: $t\bar{t}$, $W$, $t\bar{t}Z$, $WWW$, and same-sign $WW$ and backgrounds from instrumental effects due to charge misidentification. The search in Ref. [?] also utilizes jet substructure techniques to identify boosted $T_{5/3}$ topologies. These searches restrict the $T_{5/3}$ mass to be higher than 645 GeV [?], and 770 GeV[?]. The single $T_{5/3}$ production cross section depends on the coupling constant $\lambda$ of the $tWT_{5/3}$ vertex. ATLAS has performed an analysis of same-sign dileptons for the cases where $\lambda = 1$, $\lambda = 3$ which includes both the single and pair production and for $\lambda \ll 1$, which corresponds to pair production only. This analysis leads to a 95% C.L. lower limit on the mass of the $T_{5/3}$ of 0.68, 0.70, and 0.67 TeV for $\lambda = 1, 3$ and $\ll 1$ respectively.

### 2.5 Colorons, $Z'$ and Colored Scalars

These particles are associated with topcondensate and top-seesaw models, which involve an enlarged color gauge group. The new particles decay to dijets, and $t\bar{t}$ and $b\bar{b}$.

Direct searches for colorons, $W'$, $Z'$, color octect scalars and other heavy objects decaying to $q\bar{q}$, or $qg$ or $qq$ or $gg$ has been performed in the proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV, during the 2011 and 2012 running of the LHC. From analysis of dijet events, in a data sample corresponding to a luminosity of 19.6 $\mathrm{fb}^{-1}$, the CMS experiment excludes pair production of colorons with mass between $1.20 - -3.60$ and $3.90 - -4.08$] TeV at 95% CL; Color Octet Scalar (s8) with masses between $1.20 - -2.79$ TeV; $W'$ Boson with masses below 2.29 TeV and $Z'$ Boson with masses below 1.68 TeV, as shown in Fig. ??[?].

The analysis of an integrated luminosity of 5.0 $\mathrm{fb}^{-1}$ proton-proton collision data set collected at $\sqrt{s} = 7$ excluded colorons with masses between 250 GeV and 740 GeV assuming colorons decay into 100% into $q\bar{q}$[?]. This analysis is based on events with at least four jets and two dijet combinations with similar dijet mass.

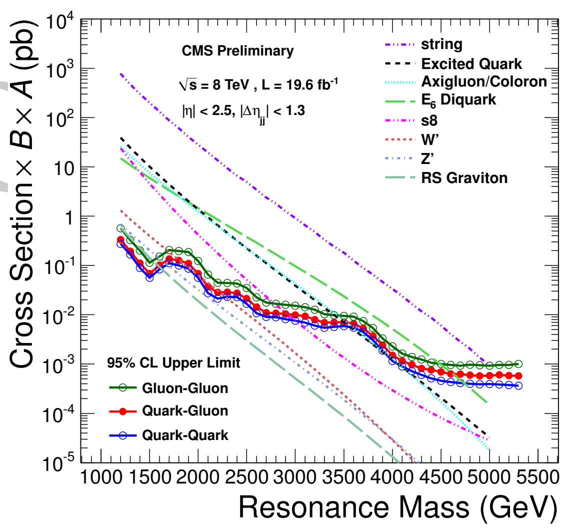


Figure 3: Observed 95% C.L. limits on $\sigma \times B \times A$ for string resonances, excited quarks, axigluons, colorons, E6 diquarks, s8 resonances, $W'$ and $Z'$ bosons, and RandallSundrum gravitons [?].

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